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High resolution and large sensing range liquid level measurement using phase-sensitive optic distributed sensor

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Abstract: Liquid level sensor with large sensing range and high-resolution is essential for the application of industry monitoring. In this work, a distributed optical fiber liquid level sensor is proposed and demonstrated based on phase-sensitive optical time domain reflectometry (φ-OTDR). In the basic of the thermal optic effect, the temperature change will induce the fluctuation of the effective refractive indexes of the fiber core, as well as the fluctuation of the optical path of the light transmitting in the fiber. Therefore, the φ-OTDR can detect the liquid level with a large measurement range by interrogating the phase information along the fiber due to the temperature difference between the liquid and air. Further, the scattering enhanced optical fiber (SEOF) is used as the sensing fiber to improve the signal to noise ratio (SNR) of the phase signal. Moreover, a high sensitivity liquid level sensing head by wrapping the SEOF on a heat conductive cylinder is designed and optimized to improve the sensing resolution. In the experiment, the proposed distributed liquid level sensor presents a high sensitivity of 73.4 rad/mm, corresponding to a competitive liquid level resolution of 142μm based on the noise floor of 10.4 rad within 160 s. The field test validates a large sensing range of 20 cm which is limited by the cylinder length, while a potential sensing range could reach 320 m with the sensing fiber of 40 km, proving a dynamic range of 127.1 dB. The proposed liquid level sensor with large dynamic range and high sensing resolution can benefit potential application in smart industry platforms and biomedicine monitoring.

1. Introduction

Liquid level sensing plays an important role in the modern industry and medical apparatus area involving monitoring oil storage, flood warning, chemical processing monitoring, and pharmaceutical development [1]. Generally, the measurement resolution and dynamic range are two key performances of the liquid level sensor. In the past years, electrical and mechanical liquid level sensors are widely utilized and present an excellent performance of large dynamic range as well as high sensing resolution [2,3]. However, the consumption of electricity limits their applications, especially for corrosive, conductive or potential explosive environments.

As an alternatively approach, optical fiber sensors pave a new way for liquid level sensing with the inherent advantages of electric isolation, anti-erosion, highly sensitive, and capability for remote monitoring. Numerous optical fiber liquid level sensors have been proposed during the past decade, which are based on highly sensitive optical structures such as fiber Bragg gratings [4,5], Fabry-Perot interferometers [6], multimode interferometers [7,8], and micro-fiber probes [9]. In general, the liquid level sensors based on interference effect rely on coupling light out the

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fiber to measure the surrounding refractive index, which can achieve a high sensing resolution but present a small sensing range [8,9]. Particularly, Junjie Wang have reported a liquid level sensor based on an optical reflective microfiber probe with ultra-high resolution of 20 μm while the linear sensing range is only 0.5 mm [9].

Recently, to extend the sensing range of the fiber optical liquid level sensor, distributed or quasi-distributed liquid level sensors have been attracted more and more research interesting for the large sensing range without blind area. Distributed liquid level sensors are developed based on the thermo-optic effect and different kinds of distributed sensing techniques, such as optical frequency domain reflectometry (OFDR) [10], Brillouin optical time domain analysis (BOTDA) [11], and chaotic optical correlation domain reflectometry (COCDR) [12]. By interrogating the temperature distribution along the sensing fiber, the liquid interface can be located through the different thermal characteristics between the air and liquid [13]. For example, Hongying Zhang has demonstrated a distributed liquid level sensor with large sensing range of 20 cm based on differential pulse-width pair BOTDA and self-heated high attenuation fiber, which presents a liquid level sensing resolution of 1 cm [11]. Therefore, although the distributed liquid level sensor can achieve a large sensing range, the sensing resolution should be further improved.

In this paper, a distributed liquid level sensor with high sensing resolution as well as large sensing range is demonstrated based on the phase sensitive optical time domain reflectometry (φ-OTDR) and thermal optic effect of fiber. Due to the different temperature of the air and the liquid, the effective refractive indexes of the fiber in air or liquid is different owing to the thermal optic effect, which will induce a phase vibration of the laser transmitting in the fiber. Therefore, the φ-OTDR can locate the liquid interface by interrogating the phase information along the fiber. Furthermore, to suppress the phase noise of the φ-OTDR, the scattering enhanced optical fiber (SEOF) with a series of scattering enhanced points (SEPs) is employed as the sensing fiber. To further improve the sensing resolution of the liquid level sensor, the SEOF is wrapped on a cylinder with optimized design as the sensing head. The proposed liquid level sensor proves a high sensing resolution of 142 μm and large sensing range of 20 cm by experiment validation, while the potential sensing range will be larger than 320 m without deteriorating the resolution in theory. The large dynamic range as well as the high sensing resolution will make the proposed liquid level sensor play an irreplaceable role in the industry monitoring applications.

2. Sensing principle

The proposed liquid lever sensor with high sensing resolution and large sensing range is realized based on φ-OTDR and special packaged scattering enhanced optical fiber (SEOF). The SEOF is fabricated by laser exposure on the single mode fiber (SMF) to inscribe a series of scattering enhanced points (SEPs) with a certain interval L [14]. The SEOF can provide scattering signals with high signal to ratio (SNR) which will be only scattered from the fixed positions [15]. The SEOF is packaged in sensing head and inserted in the liquid to sense the liquid level fluctuation. To achieve a high detection sensitivity, the liquid sensor with SEOF is interrogated by the heterodyne φ-OTDR, as illustrated in the Fig. 1. In the interrogation system, the ultra-narrow linewidth laser (NKT X15) is divided into the probe laser and local oscillator (LO) light by an optical coupler. Afterwards, the probe laser is modulated into a series of pulses and with a given light frequency shift f_d by the acoustical optical modulator (AOM). Then, the probe pulses are amplified by erbium doped fiber amplifier (EDFA) and injected into the SEOF by a circulator. Finally, the backscattered light from the SEOF is mixed with the LO light by a coupler and then received by a balanced Photodetector (BPD). The beat frequency signal output from the BPD is acquired a data acquisition card (DAQ) and demodulated into the phase change along the SEOF by the host computer.

Theoretically, the beat frequency signal interfered by the LO light and backscattering signals from the SEOF behaves as a series of beat frequency pulse trains with period dependent on the

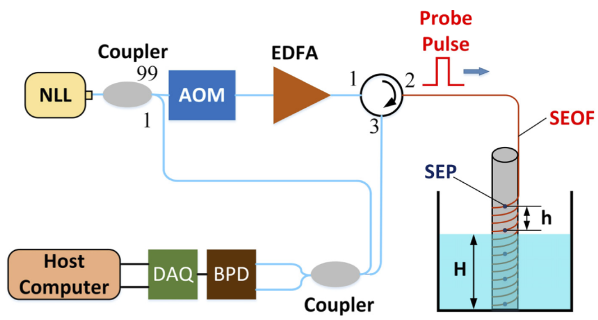

Fig. 1. Schematic diagram of the distributed liquid level sensor based on the φ-OTDR system.

SEPs interval, which can be expressed as:

$$I(t) = A \cdot \sum_{k=1}^{K} [rect(t - k \cdot \frac{n_0 L}{c}) \cdot \cos(2\pi f_d t + \varphi(k))]. \tag{1}$$

where A is the amplitude of the interference signal, K is the total number of the SEPs in the sensing fiber, n_o is the refractive index of the fiber core, c is the light speed in the vacuum, f_d is the frequency shift introduced by the AOM, and $\varphi(k)$ is the initial phase of the scattering light of the k-th SEP in the SEOF. $\varphi(k)$ can be interrogated from the backscattering beat signals by the equation as follow [16]:

$$\varphi(k) = \arctan(\frac{I_k(t) \cdot \cos(2\pi f_d t)}{I_k(t) \cdot \sin(2\pi f_d t)}). \tag{2}$$

where $I_k(t)$ is the interference signal scattering from the k-th SEP. The phase difference between two SEPs is only depended on the change of optical path, which can be obtained by subtracting the phase of (k+1)-th and k-th SPEs. Therefore, the fiber between two adjacent SEPs can be defined as a sensing unit, and the phase signals of n-th sensing unit can bes expressed blow:

$$\phi_k(n) = \varphi_{k+1}(n) - \varphi_k(n) = \frac{4\pi n_0 \nu L}{c}(\varepsilon_k + C \cdot \Delta T_k). \tag{3}$$

where ν is the optical frequency of the laser, ε_k is the strain applied on the k-th unit, ΔT_k is the temperature change of the k-th sensing unit, and C is the constant related to the phase sensitivity of temperature. When the ν is constant, the phase signal in k-th unit will be only proportional to ε_k and T. Therefore, in the proposed liquid level sensor, a part of the sensing fiber is submerged into the liquid, while the rest of sensing fiber is stay in the air. Near the interface of the liquid, the temperature of liquid is different from the temperature of air in natural state due to the liquid evaporating and different specific heat capacity of liquid and air. Therefore, the phase signals of the sensing units in the air and liquid can be respectively expressed as:

$$\phi_a(n) = \frac{4\pi \nu L n_0 C \Delta T_a}{c}, \tag{4}$$

$$\phi_l(n) = \frac{4\pi \nu L}{c} \cdot n_0(\varepsilon_l + C \cdot \Delta T_l). \tag{5}$$

where ΔT_a and ΔT_l are the temperature variation of air and liquid, respectively, and ε_l is the strain which introduced by the static pressure of the liquid. Therefore, assuming the temperature distribution of the sensing unit is uniform in the liquid or air, the phase signals of the sensing units which are completely in the air or liquid are stable. While the phase of the sensing unit at interface between the air and liquid will fluctuate sharply. Moreover, the phase variation of the sensing unit at the interface will be proportional to the fiber length immersed in the liquid. Hence, the liquid level H can be further calculated through the phase variation, which can be deduced as:

$$\boldsymbol{H = (i-1)h + \phi_i/S} \tag{6}$$

where ϕ_i is the phase signal of the i-th sensing unit at the interface, h is the height of a sensing unit wrapped on the sensing head. Here, the liquid level sensitivity S can be deduced as:

$$\boldsymbol{S = 4\pi\nu n_0 L[\epsilon + C \cdot (T_l - T_a)]/hc} \tag{7}$$

where T_a and T_l are the real-time temperature of air and liquid, respectively. Owing that the liquid level sensitivity S is relative to the temperature of the air and liquid, which should be calibrated and compensated by the sensor design.

3. Sensor design

To sense the liquid level with large sensing range and high sensing resolution, the SEOF is specially packaged in the sensing head. As shown in Fig. 2, the SEOF is helical wound on the elastic cylinder with low stress. As the sensing principle shown in the Eq. (7), the liquid level sensitivity of the sensing head is dependent on L/h. While, the height of a sensing unit h is related to the structure of the spiral packaged SEOF, which can be expressed as:

$$\boldsymbol{h = \frac{Ls}{\sqrt{(\pi D)^2 + s^2}}} \tag{8}$$

where s is the screw pitch of the spiral SEOF, and D is the diameter of the threaded cylinder. To achieve a high liquid level sensing sensitivity, the height of a sensing unit h should be small, which require a large D and small s. However, the large diameter will limit the applied range of the proposed sensor, and the screw pitch is also limited by the fiber diameter.

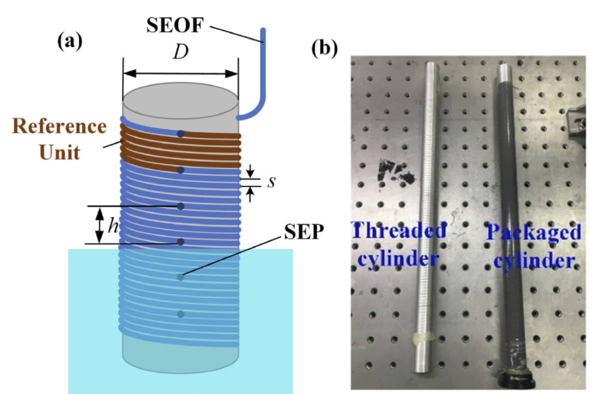

Fig. 2. (a) Structure diagram of the sensing head with SEOF; (b) Picture of the unpackaged cylinder and packaged sensing head.

Additionally, the liquid level sensitivity S is also relative to temperature. The fluctuation of temperature will induce the vibration of S, introducing an extra error for liquid lever sensing. Moreover, it has been demonstrated that the frequency shift of the laser source in φ-OTDR will also induce a low frequency phase noise [17]. Therefore, the sensing units at the top of the sensing head are served as the reference unit to record the temperature fluctuation of the cylinder.

Then, the phase vibration of reference unit is used to compensate the variation of ϕ_i and S. The liquid level H interrogated by the liquid level sensor can be compensated by the follow:

$$\boldsymbol{H} = (\boldsymbol{i}-\mathbf{1})\boldsymbol{h} + (\boldsymbol{\phi_i} - \boldsymbol{\phi_r})/(\boldsymbol{S}\cdot\boldsymbol{C_r}\cdot\boldsymbol{\phi_r}) \tag{9}$$

where ϕ_r is the phase signal of the reference unit, and the C_r is the compensation coefficient which can be calibrated by the experimental. For the distributed phase sensitive liquid level sensor, the sensing range is only limited by the transmission loss of the SEOF. While the sensing resolution of the proposed liquid level sensor is dependent on the phase noise floor of each sensing unit. Therefore, the proposed liquid level sensor can achieve a high resolution and large sensing range at the same time.

For experimental test, 35 meter SEOF which contains 7 SEPs with reflectivity of -50 dB and interval length of 5 m is wrapped on a treaded cylinder. The SEP can provide a stable reflected signal along with low insert loss. The diameter of the treaded cylinder is 50 mm, and the screw pitch of the wrapped fiber is 1.25 mm. Therefore, the height of one sensing unit is about 40 mm, corresponding to the total sensing length of 240 mm. Specifically, the SEOF is fabricated based on bend insensitive SMF to reduce the transmission loss after package. Then, the packaged sensing head is coated with thermally conductive silicon rubber to protect the fiber and improve the thermal sensitivity of the sensing fiber.

4. Experimental results and discussion

In the experiment, the sensing head wrapped with SEOF is installed in the liquid container, and the bottom of the sensing head is high than the bottom of liquid container with 170 mm. After injecting the probe laser pulses with width of 30 ns, the scattering beat signals, and the amplitude of beat signals are plotted in the Fig. 3. The scattering signals from the SEPs are much stronger than the Rayleigh backscattering light and possess a high SNR. Two adjacent beat frequency compose into a sensing unit, whose phase vibration is only dependent on the liquid interface fluctuation at that sensing unit.

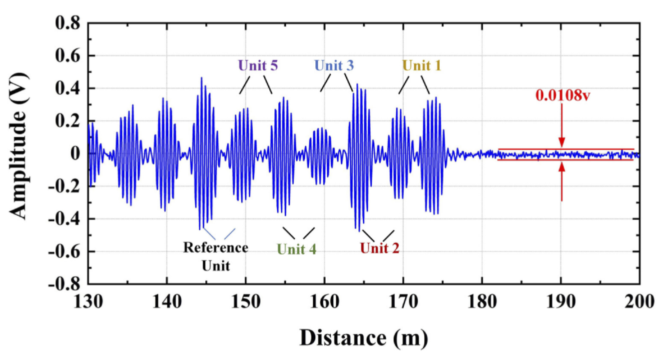

Fig. 3. The beat signals scattering from the sensing head.

To validate the proposed distributed liquid level sensor, the pure water is injected into the liquid container to adjust the liquid level with the injection velocity of 0.33 mm/s. The room temperature during the experiment is 24.5 °C, and the temperature of the pure water is 23.7 °C. The phase variation of the sensing unit in the sensing head during the injection process of water is depicted in Fig. 4(a). After injecting the water, the phase signals of different sensing units have slight fluctuation, which is induced by the temperature variation of the threaded cylinder. When the sensing unit 1 at the bottom of the sensing head is gradually inserted into the water, the phase signal change rapidly due to the directly temperature coupling with water. When the sensing unit

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is completely immersed in the water, the phase curve becomes flat again, and the phase signal of the adjacent sensing unit variates quickly due to the water immersed. Therefore, the liquid interface can be located by finding the sensing unit which fluctuates rapidly.

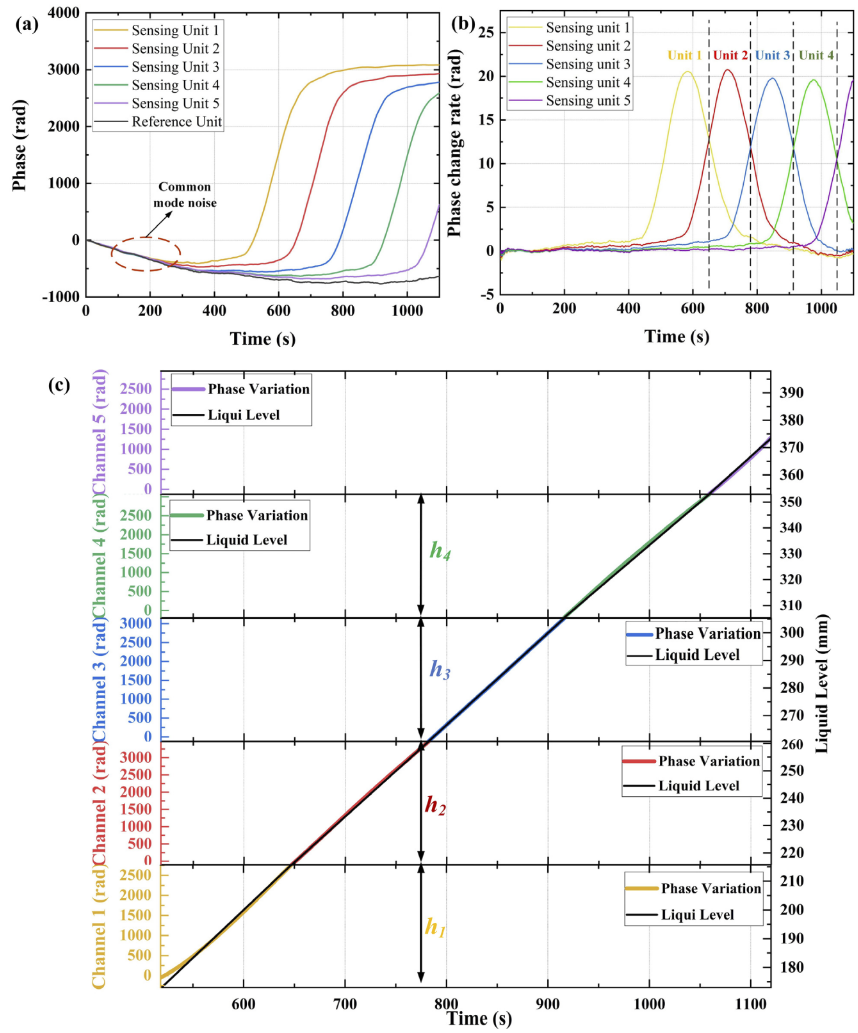

Fig. 4. (a) Original phase signal of the sensing units in the sensing head; (b) Sensing unit location based on phase change rate. (c) Phase signal of each sensing unit during water immersing.

However, when the liquid interface approach to the interface of two adjacent channels, the phase signal of two adjacent channels will present phase overlap as shown in Fig. 4(a), which is induced by the temperature crosstalk between two adjacent channels. The phase overlap between two adjacent channels can be separated by the phase change rate of two sensing channels. When the liquid interface moves cross the interface of two adjacent sensing channels, the phase change rate of the sensing channel at the liquid interface will be larger than the channels which is completely immersed by the liquid. Therefore, the liquid level can be located by the phase change rate of each sensing channel, as illustrated in Fig. 4(b).

It can be seen the phase change of a single sensing unit is not a linear relationship, which is induced by the temperature crosstalk with the adjacent sensing unity. To improve the sensing

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linearity of the liquid sensor at the interface of two adjacent channels, the spatial moving averaging algorithm is adopted to reduce the phase overlap. The phase signal of a sensing unit is compensated by the two adjacent sensing unit. As an example, the phase of the sensing unit 2 is averaging with the phase signals of sensing unit1 and sensing unit 3. After compensating, the phase signals of each sensing unit become to linearity. To exhibit the variation trend of the phase signals with liquid level change, the phase signals of each sensing unit during water immersed process with initial liquid level of 173 mm are plotted in Fig. 4(c), respectively. It can be observed the phase signal of each sensing unit is proportional to the increasing liquid level from 173-374 mm.

To calibrate the phase sensitivity S of the liquid level sensor, the sensing unit 3 is selected as an example and applied with a liquid level change. The sensor was tested by 3 times with same liquid level change. The relationship of the average phase value of sensing unit 3 and liquid level in this section is analyzed and depicted in the Fig. 5, which exhibit a linearly relationship. The maximum standard deviation for 3 tests is 15.1 rad, which presents a high level of reproducibility. The phase sensitivity of the liquid level sensor is 73.4 rad/mm with R-Square of 0.9999. The high linearity of the phase sensitive liquid level sensor can ensure a high sensing precision.

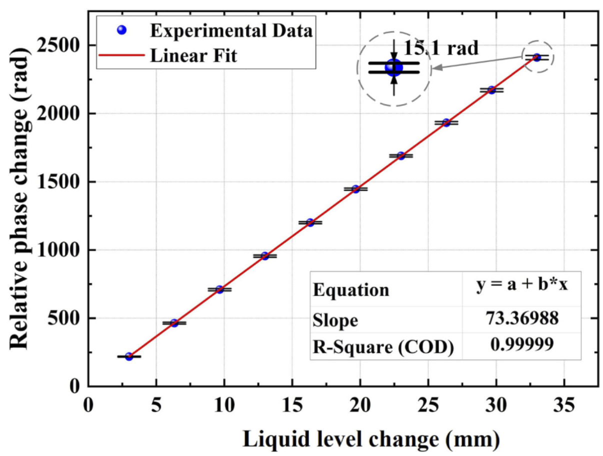

Fig. 5. Relationship between the phase vibration and the liquid level change.

As discussion above, the phase signal of the proposed liquid level sensor will be influenced by the common mode phase noise, which is induced by the laser frequency shift and temperature variation. As illustrated in the Fig. 4(a), the phase curve of all the sensing unit will fluctuate with the same tendency before the water injection, which will ruin the sensing resolution of the liquid level sensor. However, the phase curve of the reference unit at the top of sensing head also presents a same common mode phase noise, which can be used to compensate the other sensing unit. After compensation, the phase noise of the sensing units in the air are suppressed during the water injection as illustrated in Fig. 6(a). From the enlarged view of the rectangular box as shown in Fig. 6(b), the maximum fluctuation amplitude of the phase noise in 160 second is small than 10.4 rad. Considering that the sensitivity of the phase sensitivity liquid level sensor is about 73.4 rad/mm, the resolution of the liquid level senor is superior to 142 μm.

Although only 20 cm sensing range is demonstrated under the laboratory condition, it can be greatly extended in the practical applications. Combining the sensing resolution of 142 μm, the phase sensitive liquid level sensor possesses a large sensing dynamic with 62.97 dB for experimental demonstration, which is the ratio between the sensing range and sensing resolusion. Theoretically, the SEOF based phase sensitive distributed sensor can interrogate the sensing fiber longer than 40 km with a high SNR, corresponding to a liquid level sensing range of 320 m with

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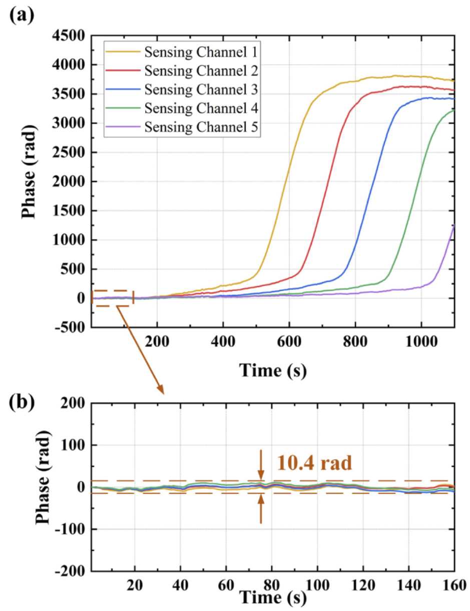

Fig. 6. (a) Phase signal after common-mode noise compensation by the reference unit. (b) Phase noise before water injection.

proposed sensing head. Moreover, the sensing resolution is only dependent on the phase noise of one sensing unit, which will be not affected by the sensing range. Therefore, the proposed liquid level sensor can possess a potential sensing range of 320 m with a high resolution of 142 μm, showing an ultra-large potential sensing range over 127 dB.

Table 1 presents the comparison of the performance between the proposed distributed liquid level sensor and various reported fiber based liquid level sensors. Compared with the other liquid level sensor, the proposed liquid level sensor presents the largest sensing range, which is 64 times higher than the liquid level sensor based on the Fiber extrinsic Fabry–Perot interferometer. Moreover, the proposed liquid level sensor possesses the highest sensing resolution in the liquid

Table 1. Sensing resolution and sensing range of several liquid level sensor

Method	Resolution (mm)	Sensing Range (mm)	Dynamic Range (dB)
Polymer fiber Bragg gratings [5]	2	750	51.5
Fiber extrinsic Fabry–Perot interferometer [6]	0.7	5000[a]	77[b]
No-core fiber [7]	0.045	45	60
Hollow core fiber [8]	7×10^{-4}	4.7	76.5
Reflective microfiber probe [9]	2×10^{-4}	0.5	68
Luna OFDR and heater wire [10]	5	220	32.86
DPP-BOTDA and self-heated high attenuation fiber [11]	10	200	26
Optically absorbing vanadium doped optical fiber and FPI [13]	3	1000	50.45
This work	0.142	200 / 320000[a]	62.91 / 127.1[b]

[a]Potential sensing range in theory.
[b]Potential dynamic range in theory.

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level sensor whose sensing range larger than 100 mm. Significantly, it is the first reported a sub-mm resolution with ultra-large potential sensing dynamic range over 120 dB for liquid level sensing, to the best of our knowledge. The competitive performances make the liquid level sensor has potential applications in smart industry platform.

5. Conclusion

We have demonstrated a high resolution and large dynamic liquid level sensor based on the φ-OTDR technology and thermal optic effect. The liquid level can be detected by interrogating the phase distribution along the fiber due to the different temperature of liquid and air. To demodulate the phase signal with high quality, the SEOF is employed as the sensing fiber to suppress the fading noise of the φ-OTDR. Moreover, a highly sensitive sensing head by wrapping the SEOF on the thermal conductive cylinder is introduced to improve the sensing resolution. The experimental results indicate that the proposed liquid level sensor a sensing resolution of 142 μm is realized, which will not be affected by the sensing range. Moreover, the proposed liquid level sensor presents a potential large sensing range of 320 m with no resolution degeneration in theory, corresponding to large sensing dynamic range of 127 dB. The large sensing dynamic as well as the high sensing resolution will make the proposed liquid level sensor play an irreplaceable role in the industry monitoring applications.

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